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LIQUID INFLOW TO PARTIALLY FULL, HEMISPHERICAL-ENDED CYLINDERS DURING WEIGHTLESSNESS

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Cleveland, Ohio

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16. Abstract

The behavior of the liquid-vapor interface during liquid inflow to a hemispherical ended cylinder during weightlessness was observed. The tank was partially full of liquid at the initiation of inflow, and the investigation was limited to two tank radii (2 and 4 cm), one inlet line radius (0.2 cm), and two liquids (trichlorotrifluoroethane and ethanol). Both a stable region and an unstable region of interface behavior were noted. Results indicate that the interface becomes unstable above a critical inflow velocity. This critical inflow velocity appears to remain constant for a given liquid until a certain initial liquid height has been exceeded. At initial liquid heights larger than this value, the critical inflow velocity increases slightly. The rate of increase was larger for ethanol than for trichlorotrifluoroethane.

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SUMMARY

An experimental investigation was conducted in which the behavior of the liquid-vapor interface during liquid inflow to a hemispherical ended cylinder during weightlessness was observed. The cylinder was partially full of liquid at the initiation of inflow and the investigation was limited to two tank radii (2 and 4 cm), one inlet line radius (0.2 cm) and two liquids (trichlorotrifluoroethane and ethanol). Both a stable region and and unstable region of interface behavior were noted. Results indicate that the liquid-vapor interface becomes unstable above a critical inflow velocity. This critical inflow velocity appears to remain constant for a given liquid until a certain initial liquid height has been exceeded. At initial liquid heights larger than this value, the critical inflow velocity increases slightly. The rate of increase was larger for ethanol than for trichlorotrifluoroethane.

INTRODUCTION

In-orbit propellant transfer (refueling) and the transfer of liquids between containers as in regenerative life-support systems will be required for future long range space missions. A knowledge of both the outflow characteristics from a storage tank and the subsequent fluid behavior during filling of the receiver tank under weightlessness is required for the design of these transfer systems. The Lewis Research Center is currently conducting a program studying both these phenomena.

Previous work by this author was concerned with the filling of a hemispherical ended cylinder which was initially void of liquid, as might be the case for an in-orbit refueling of the empty propellant tanks of a space vehicle (ref. 1). In that study, both a stable interface characterized by relatively little interface distortion and an unstable interface

characterized by a large degree of interface distortion were observed. Furthermore, the stability of the liquid-vapor interface was delineated by a Weber number based on the inlet line radius and the inflow velocity.

In regenerative life-support systems, it is likely that the transfer of liquids may occur when the receiver tanks are not totally void of liquid. Therefore, an extension of the previous work would consist of an investigation of the behavior of the liquid-vapor interface during the filling of a hemispherical ended cylinder which contained a certain quantity of liquid at the initiation of inflow. This report presents a photographic study of the inflow process under such conditions. The general behavior of the liquid-vapor interface is discussed and compared with that for a tank of the same geometry, which is initially void of liquid. The study was conducted in the Center's 2.2-Second Drop Tower Facility and was limited to two test liquids (ethanol and trichlorotrifluoroethane), one inlet line radius (0.2 cm), and two tank radii (2 and 4 cm).

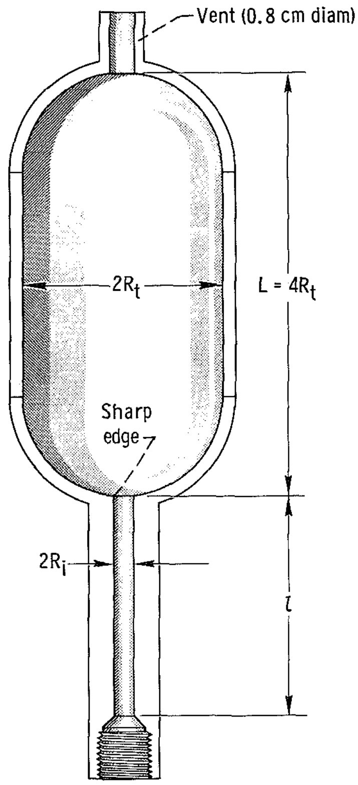
SYMBOLS

h_{og}	height of zero-gravity liquid vapor interface above the inlet line, cm
L	tank length, cm
l	inlet line length, cm
Re_j	jet Reynolds number, $\frac{\rho V_{i,av} R_i}{\mu}$
R_i	inlet line radius, cm
R_j	jet radius, cm
R_t	tank radius, cm
t	time during weightless drop, sec
$V_{i,av}$	average inflow velocity, cm/sec
We	Weber number, $\frac{\left(V_{i,av}\right)^2 R_i^2}{2\beta R_j}$
β	specific surface tension, σ/ρ, cm^3/sec^2
μ	viscosity, g/cm-sec
ρ	density, g/cm^3
σ	surface tension, dynes/cm; N/cm

APPARATUS AND PROCEDURE

The experimental investigation was conducted in the Lewis 2.2-Second Drop Tower Facility. A complete description of this facility, the experiment package, and the test procedure can be found in the appendix.

The experiment tanks (fig. 1) used in this investigation were hemispherical-ended cylinders machined from cast acrylic rod and then polished for photographic purposes. Inlet lines had a straight run of at least 20 radii and terminated with a sharp edge.



Tank radius, R_t, cm	Inlet line radius, R_i, cm	Inlet line length, l, cm
2	0.2	4
4	.2	8

CD-9628-13

Figure 1. - Typical experiment tank.

Tanks were open to the atmosphere through a vent located opposite the inlet line and along the longitudinal axis of the tank.

The two test liquids employed were ethanol and trichlorotrifluoroethane. Their properties pertinent to this study are given in table I. Both liquids had an essentially zero degree static contact angle with cast acrylic plastic so as to duplicate the static contact angle of most spacecraft liquids on tank materials. In order to improve photographic quality, a small amount of dye which had no measurable effect on pertinent fluid properties was added to each liquid.

TABLE I. - PROPERTIES OF TEST LIQUIDS

[Contact angle with cast acrylic plastic in air, 0^{o}.]

Liquid	Surface tension at 20^{o} C, σ, dynes/cm (or 10^{-5} N/m)	Density at 20^{o} C, ρ, g/cm^3	Viscosity at 20^{o} C, μ, g/cm-sec	Specific surface tension, β, cm^3/sec^2
Anhydrous ethanol	22.3	0.79	1.2×10^{-2}	28.3
Trichloro-trifluoro-ethane	18.6	1.58	0.7×10^{-2}	11.8

DATA REDUCTION

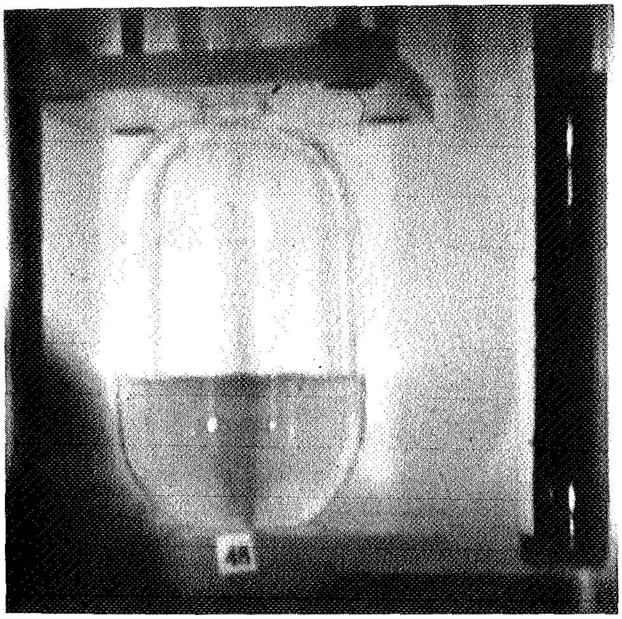
All data were recorded photographically with a high-speed camera. Flow out of a graduated cylinder and into the experiment tank could be determined directly by reading the liquid level in the graduated cylinder and a digital clock during the inflow process. By taking readings at small time increments, the average inflow velocity was calculated and was found to remain constant throughout the test.

RESULTS AND DISCUSSION

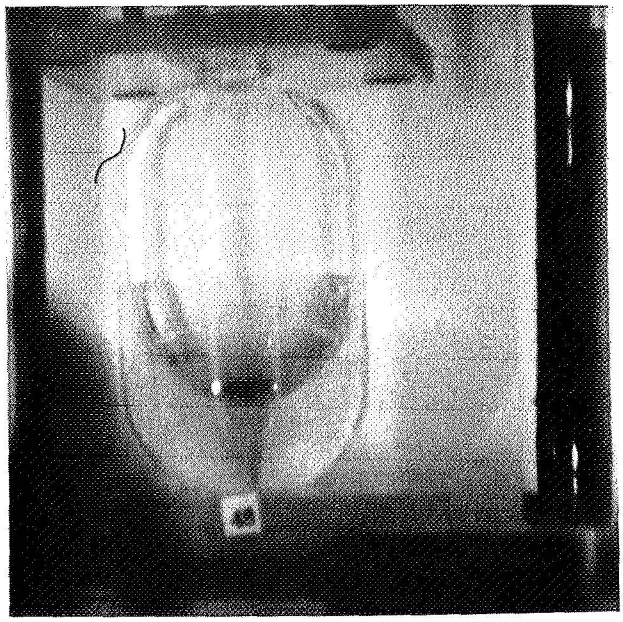
Description of Interface Behavior

As in the case of a tank which was initially void of liquid (ref. 1), both a stable region and an unstable region of interface behavior were noted:

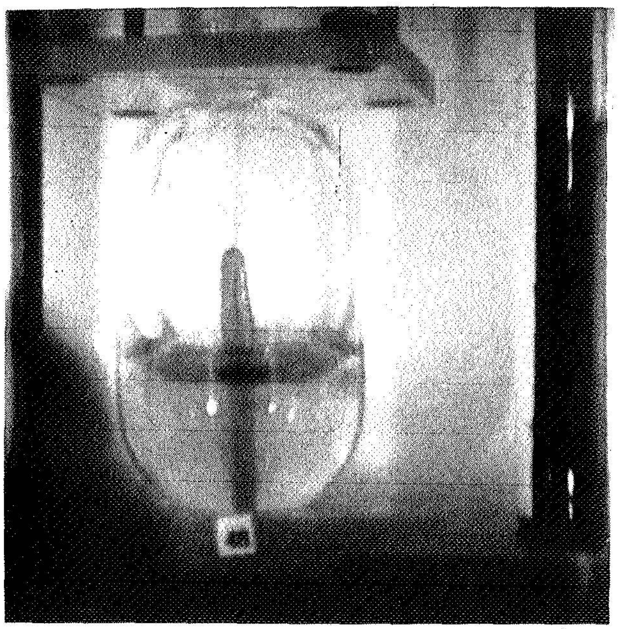
(1) In the stable region, the incoming liquid formed a small geyser at the liquid surface directly above the inlet line location. This small geyser (the largest observed geyser in this stable region was about 3 cm high) either remained at the same height or decreased in height with respect to the lowest point on the liquid-vapor interface during the inflow process. Thus, the incoming liquid was successfully being retained and collected at the inlet end of the tank. This type of behavior is shown in figure 2. The first photograph in each sequence shows the liquid-vapor interface in its normal-gravity configuration prior to the test, the second shows the zero-gravity configuration, and the last two, the interface as it appears during liquid inflow. The interface in both tests has been flattened considerably by the incoming liquid jet.



Configuration in normal gravity; drop time, 0 second.



Configuration in weightlessness before inflow; drop time, 0.32 second.

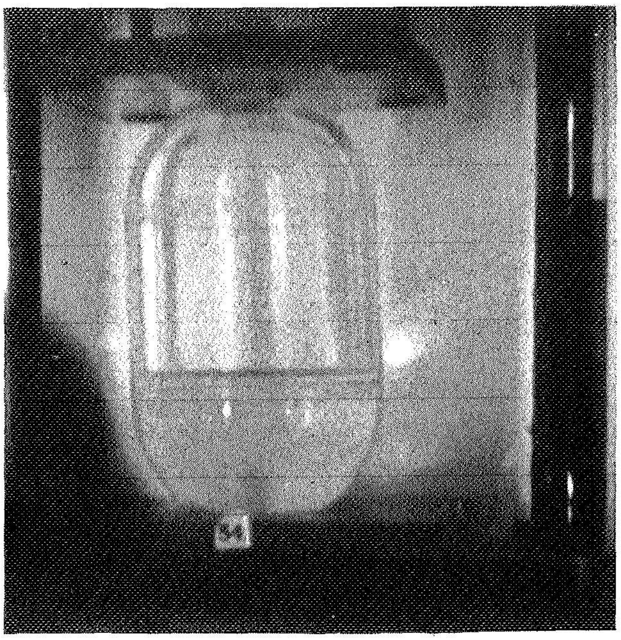


Configuration during inflow; drop time, 1.47 seconds.

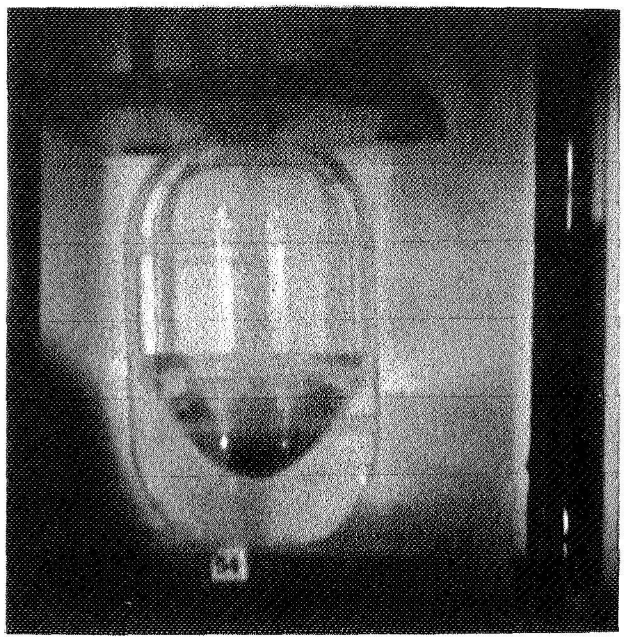
Configuration near termination of test; drop time, 2.15 seconds.

(a) Ethanol; average inflow velocity, 18.3 centimeters per second.

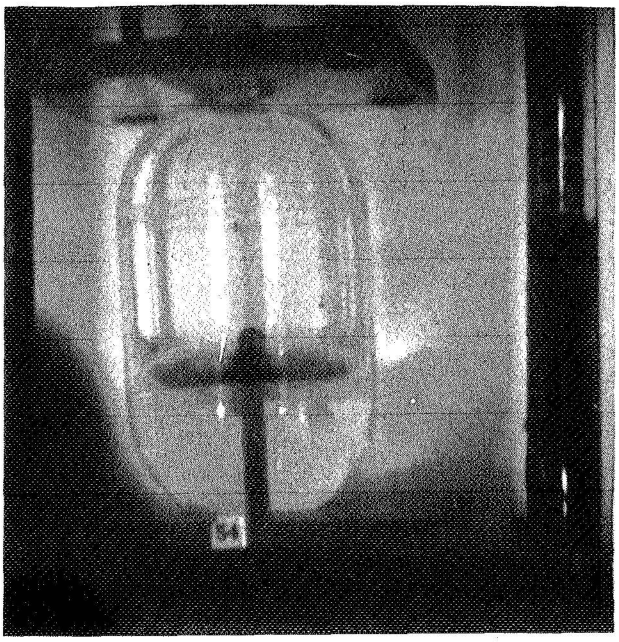
Figure 2. - Stable interface behavior. Tank radius, 2 centimeters; inlet line radius, 0.2 centimeter; height of liquid above inlet, 1.83 centimeters.



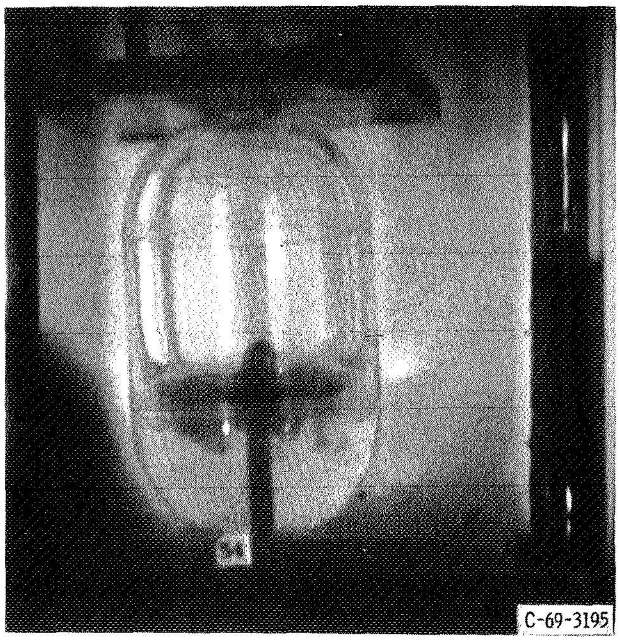
Configuration in normal gravity; drop time, 0 second.



Configuration in weightlessness before inflow; drop time, 0.60 second.



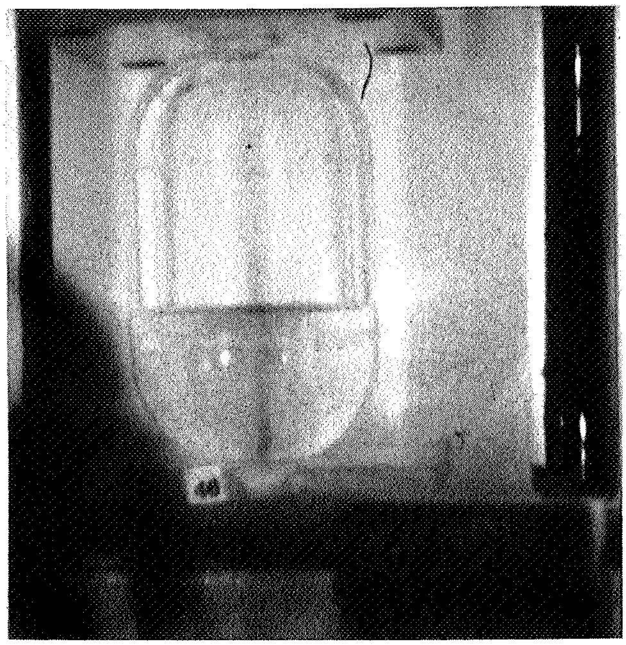
Configuration during inflow; drop time, 1.70 seconds.



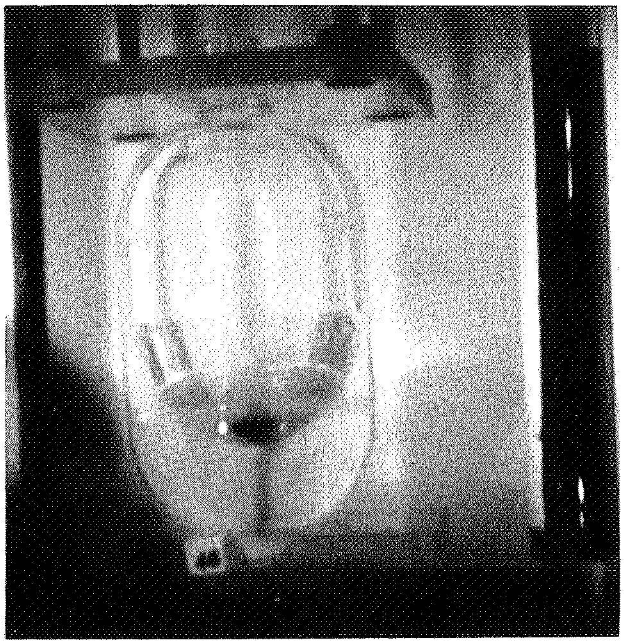
Configuration near termination of test; drop time, 2.10 seconds.

(b) Trichlorotrifluoroethane; average inflow velocity, 11.4 centimeters per second.

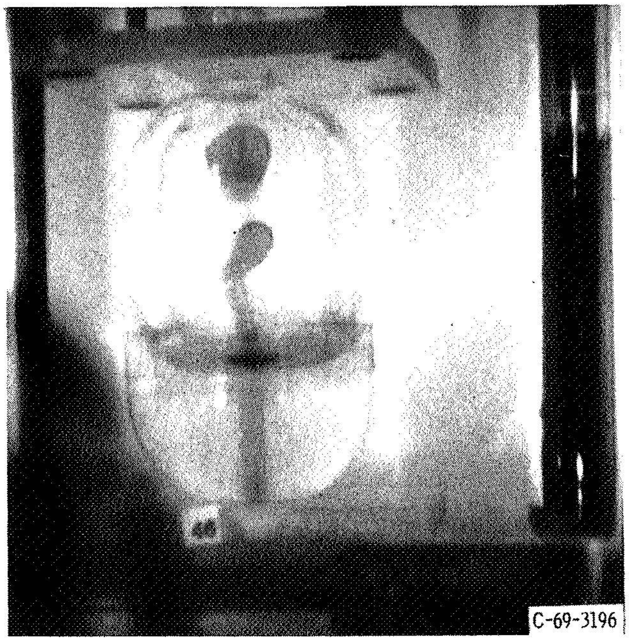
Figure 2. - Concluded.



Configuration in normal gravity; drop time, 0 second.



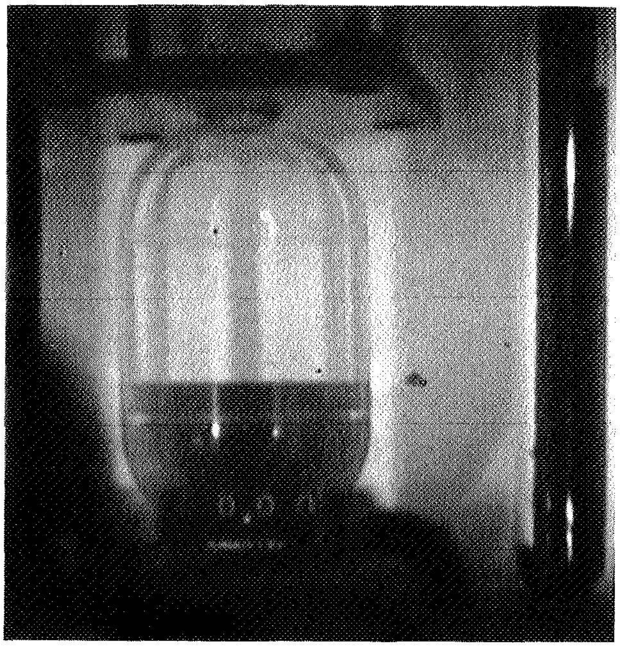
Configuration in weightlessness before inflow; drop time, 0.30 second.



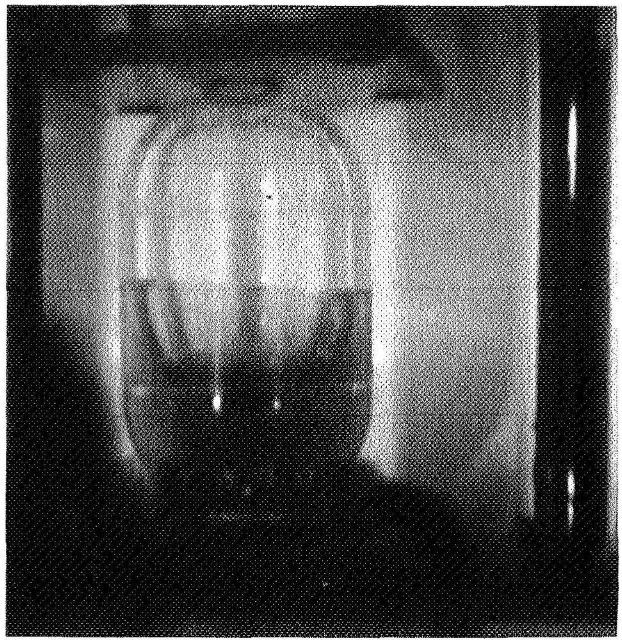
Configuration near termination of test; drop time, 2.10 seconds.

(a) Ethanol; average inflow velocity, 18.5 centimeters per second.

Figure 3. - Unstable interface behavior. Tank radius, 2 centimeters; inlet line radius, 0.2 centimeter; height of liquid above inlet, 1.83 centimeters.



Configuration in normal gravity; drop time, 0 second.



Configuration in weightlessness before inflow; drop time, 0.63 second.

Configuration near termination of test; drop time, 2.18 seconds.

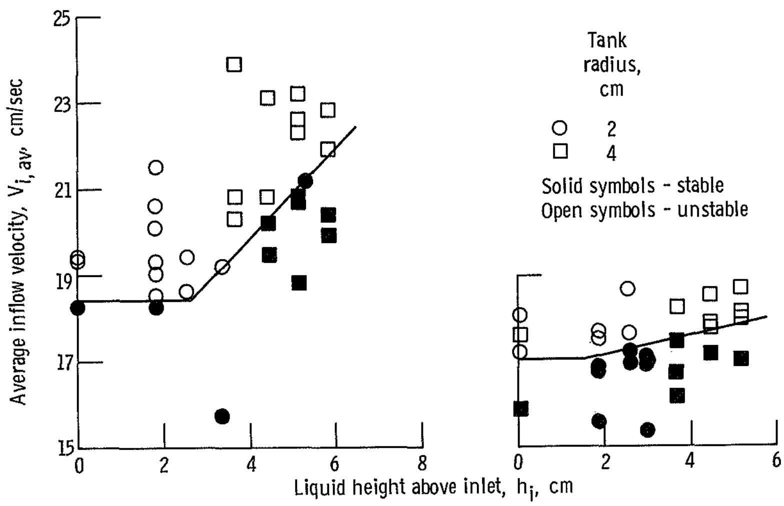
(b) Trichlorotrifluoroethane; average inflow velocity, 13.2 centimeters per second.

Figure 3. - Concluded.

(2) In the unstable region, the incoming liquid again formed a geyser directly above the inlet line. However, in this region, the geyser continued to grow in height with respect to the lowest point on the liquid-vapor interface throughout the duration of the test. In most tests, the geyser remained a continuous column of liquid, but in other tests, the geyser broke up into drops which moved toward the vent end of the tank. In these tests, only a small portion of the incoming liquid was collected at the inlet end of the tank, and continuation of the inflow process would have resulted in liquid impinging on the vent. This type of behavior is evidenced in figure 3. Note once again that the interface has been flattened by the incoming liquid jet.

Effect of Initial Liquid Height

In order to illustrate the effect of initial liquid height, inflow velocity is plotted against the liquid height above the inlet line in figure 4. (The liquid height is measured from the top of the inlet line to the lowest point on the zero-gravity liquid-vapor interface at the initiation of inflow.) The critical inflow velocity cannot be increased over that for inflow to a tank which is initially void of liquid (i.e., zero initial liquid height in fig. 4) until a certain height of liquid is located above the inlet. This initial height appears to be 13 inlet line radii for ethanol and approximately 7 inlet line radii for trichlorotrifluoroethane. Above these heights, the critical inflow velocity (i.e., the velocity above which instability occurs) for each liquid increases slightly. As can be seen in figure 4, the rate of change of critical inflow velocity with increasing liquid height is greater for ethanol that for trichlorotrifluoroethane. The velocity for ethanol increases



(a) Ethanol. (b) Trichlorotrifluoroethane.

Figure 4. - Effect of initial liquid height on critical inflow velocity.

at a rate of about 1 centimeter per second per centimeter of liquid height, while the velocity for trichlorotrifluoroethane increases at a rate of about 0.4 centimeter per second per centimeter of liquid height. Although the ratio of these rates of change corresponds to the ratio of the specific surface tensions of the liquids, it should be noted that this may be coincidental because no direct correlation was obtained.

Effect of Tank Size

Although the investigation was somewhat limited by formation time restrictions on absolute tank size (see appendix), some general observations can be made from examining the experimental data. For the two tank sizes tested, one having a radius of 2 centimeters and the other a radius of 4 centimeters, essentially the same critical inflow velocity was obtained (see fig. 4) at comparable initial liquid heights above the inlet. Thus, there was no effect due to a doubling of the tank size over the limited range of variables employed in this study.

Weber Number Criterion

An earlier study (ref. 1) has shown that a Weber number was useful in predicting the interface stability in weightlessness during liquid inflow to an initially empty hemispherically ended cylinder. The Weber number, which is a ratio of the inertia to the capillary forces, was defined therein as

$$\mathrm{We} \propto \frac{V_{i,av}^2 R_i}{2\beta} \tag{1}$$

When this grouping of experimental parameters was less than 1.3, the liquid-vapor interface was stable, and when this value is exceeded, the interface was unstable. This stability criterion should also be applicable to partially full, hemispherical-ended cylinders, provided that the incoming jet does not spread appreciably before reaching the liquid-vapor interface. If the jet does begin to spread due to viscous shear, a similar analysis (see ref. 1) assuming no change in momentum (constant pressure) would yield

$$\mathrm{We} \propto \frac{V_{i,av}^2 R_i^2}{2R_j\beta} \tag{2}$$

where R_j is the radius of the liquid jet at the liquid-vapor interface. For the condition

in which the tank is initially void of liquid, $R_j = R_i$, and equation (2) is identical to equation (1).

Unfortunately, it was not possible to measure the radius of the jet in these experiments or to obtain the angle of spread associated with a given test. However, if it is assumed that the critical value of the Weber number is again 1.3, it is possible to estimate an angle of spread associated with each liquid and inlet size. This is done by first calculating the jet radius R_j as a function of liquid height above the inlet by substituting the experiment data into equation (2).

Such calculations indicate that for ethanol, no appreciable spreading would occur for initial heights less than about 13 inlet line radii. After this initial height of liquid has been exceeded, the jet would spread at about $1\frac{1}{2}^{\circ}$ either side of the centerline. For trichlorotrifluoroethane, no spreading would occur until the initial height of liquid has exceeded about 7 inlet line radii, after which the jet would spread about 1° either side of the jet centerline.

The theoretical and experimental work of Rouse (refs. 2 and 3) shows that, if the Reynolds number is high (nominally above 1500) and the initial velocity profile of the jet is flat or square, jet spreading occurs on a molar level and the angle of spread will be about 12° to 14° either side of the jet centerline. On the other hand, if the Reynolds number is low and, in the author's opinion, if the initial velocity profile is parabolic or nearly parabolic, the rate of expansion will be due solely to molecular diffusion or viscous shear and will be relatively small or considerably less than the 12° to 14° found at high Reynolds numbers.

The Reynolds numbers associated with the tests conducted in this experiment are relatively low (nominally 250 to 700), the flow is laminar, and the initial velocity profiles are parabolic or nearly parabolic; therefore, the angle of spread in these tests should then be considerably less than the 12° to 14° quoted by Rouse. Since the calculated values (assuming a Weber number correlation) were on the order of 1° to 2°, some weight is added to the assumption that the initial value of the Weber number is 1.3 for inflow to partially filled hemispherical ended tanks.

SUMMARY OF RESULTS

An experimental investigation to determine the stability of the liquid-vapor interface during liquid inflow to a partially filled hemispherically ended cylindrical tank was conducted in a weightless environment. The liquid-vapor interface was observed over a range of initial liquid heights at various inflow velocities for one inlet size (0.2-cm radius), two tank sizes (2- and 4-cm radius), and two liquids, ethanol and trichlorotrifluoroethane. In all tests the Reynolds number (based on inlet dimensions) was low

(nominally 250 to 700) and the velocity profile was nearly parabolic. The following conclusions were made:

1. Both a stable region and an unstable region of interface behavior were noted. In the stable region, liquid collected above the inlet line and relatively little interface distortion occurred, while in the unstable region, the incoming liquid formed a geyser which moved toward the tank vent and only a small quantity of liquid collected over the inlet line.

2. The critical inflow velocity (the velocity above which the interface becomes unstable) appears to remain constant until the initial liquid height in the tank has reached a level of approximately 13 inlet line radii for ethanol and approximately 7 inlet line radii for trichlorotrifluoroethane.

3. At initial heights larger than these values, the critical inflow velocity can be increased slightly and appears to increase at a faster rate for ethanol than for trichlorotrifluoroethane.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 22, 1969,
124-09.

APPENDIX - APPARATUS AND PROCEDURE

Test Facility

The experimental data for this study were obtained in the Lewis Research Center's 2.2-Second Zero Gravity Facility. A schematic diagram of this facility is shown in figure 5. The facility consists of a building 6.4 meters (21 ft) square by 30.5 meters (100 ft) tall. Contained within the building is a drop area 27 meters (89 ft) long with a cross section of 1.5 by 2.75 meters (5 by 9 ft).

The service building has, as its major elements, a shop and service area, a calibration room, and a controlled environment room. Those components of the experiment which require special handling are prepared in the facility's controlled environment room. This airconditioned and filtered room (shown in fig. 6) contains an ultrasonic cleaning system and the laboratory equipment necessary for handling test liquids.

Mode of operation. - A 2.2-second period of weightlessness is obtained by allowing the experiment package to free fall from the top of the drop area. In order to minimize drag on the experiment package, it is enclosed in a drag shield, designed with a high ratio of weight to frontal area and a low drag coefficient. The relative motion of the experiment package with respect to the drag shield during a test is shown in figure 7. Throughout the test the experiment package and drag shield fall freely and independently of each other; that is, no guide wires, electrical lines, etc., are connected to either. Therefore, the only force acting on the freely falling experiment package is the air drag associated with the relative motion of the package within the enclosure of the drag shield. This air drag results in an equivalent gravitational acceleration acting on the experiment, which is estimated to be below 10^{-5} g's.

Release system. - The experiment package, installed within the drag shield, is suspended at the top of the drop area by a highly stressed music wire which is attached to the release system. This release system consists of a double-acting air cylinder with a hard steel knife attached to the piston. Pressurization of the air cylinder drives the knife edge against the wire which is backed by an anvil. The resulting notch causes the wire to fail, smoothly releasing the experiment. No measurable disturbances are imparted to the package by this release procedure.

Recovery system. - After the experiment package and drag shield have traversed the total length of the drop area, they are recovered after decelerating in a 2.2-meter (7-ft) deep container filled with sand. The deceleration rate (averaging 15 g's) is controlled by selectively varying the tips of the deceleration spikes mounted on the bottom of the drag shield (fig. 5). At the time of impact of the drag shield in the decelerator container, the experiment package has traversed the vertical distance within the drag shield (compare figs. 7(a) and (c)).

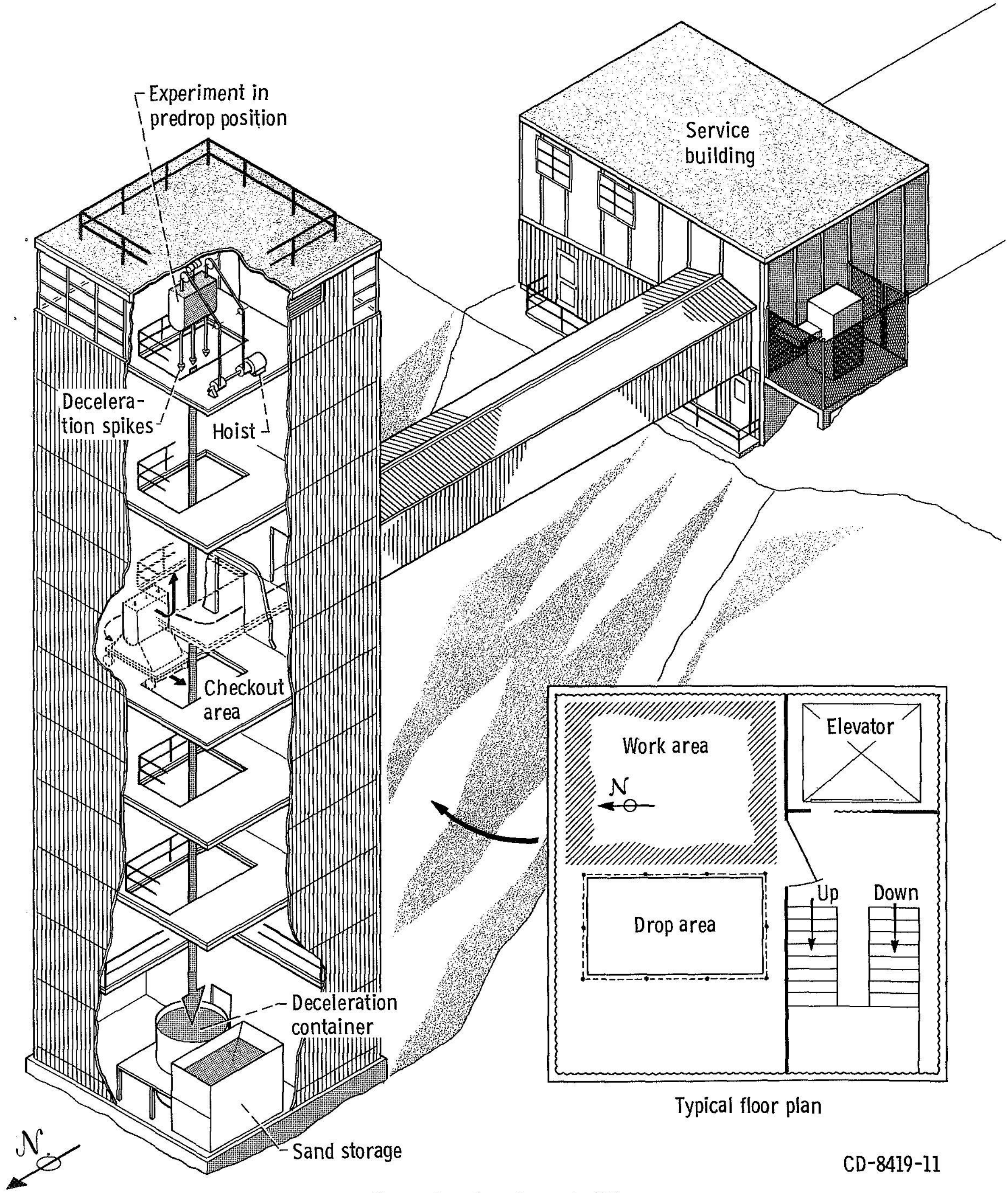
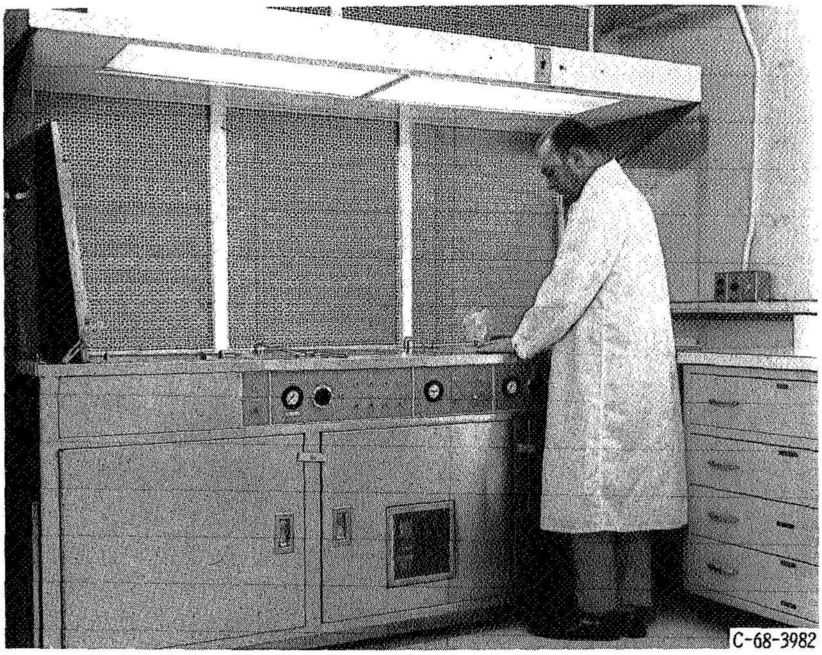
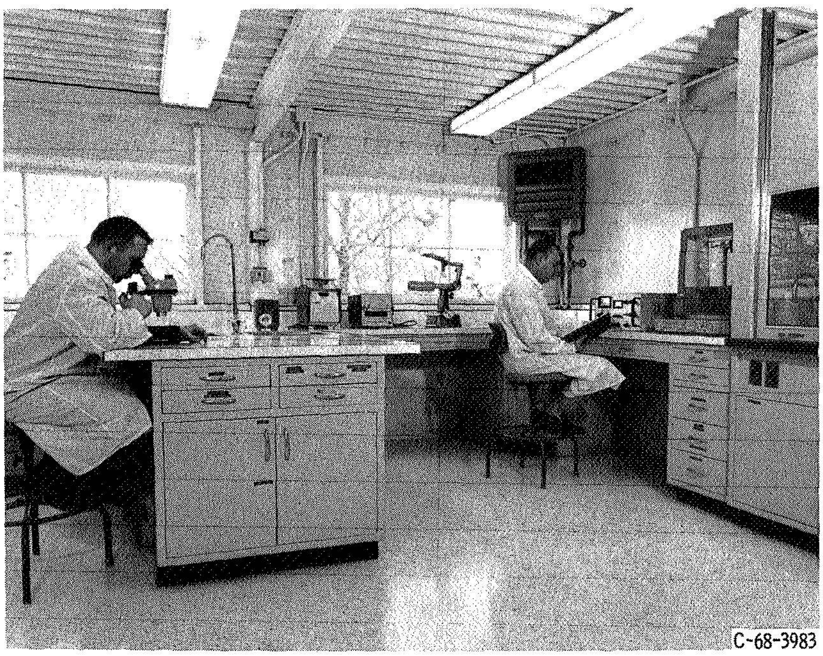


Figure 5. - Drop tower facility.



(a) Ultrasonic cleaning system.



(b) Laboratory equipment.

Figure 6. - Controlled environment room.

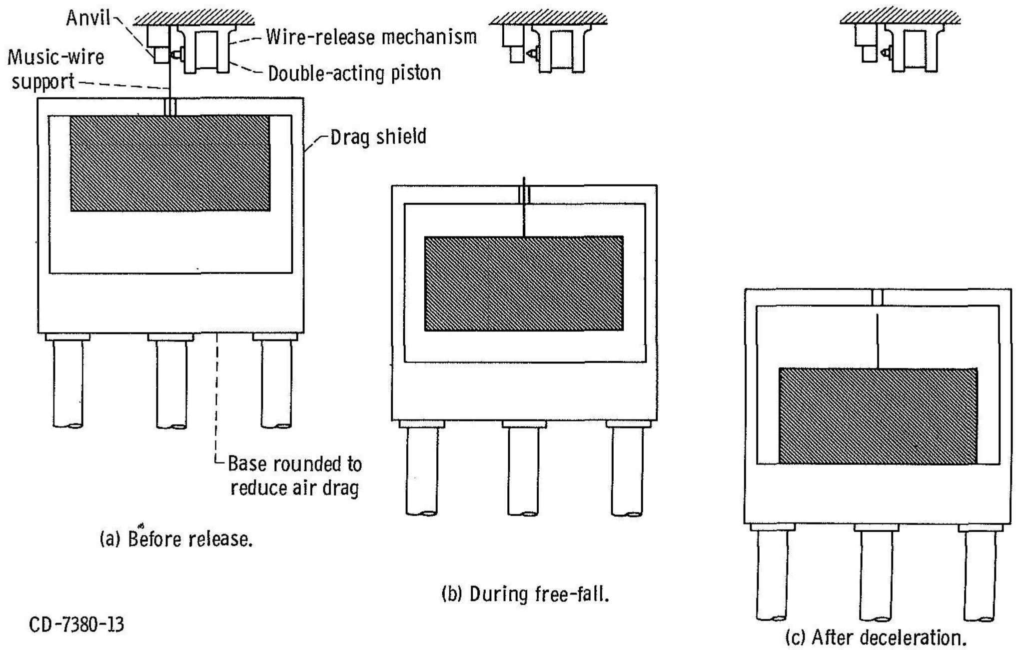


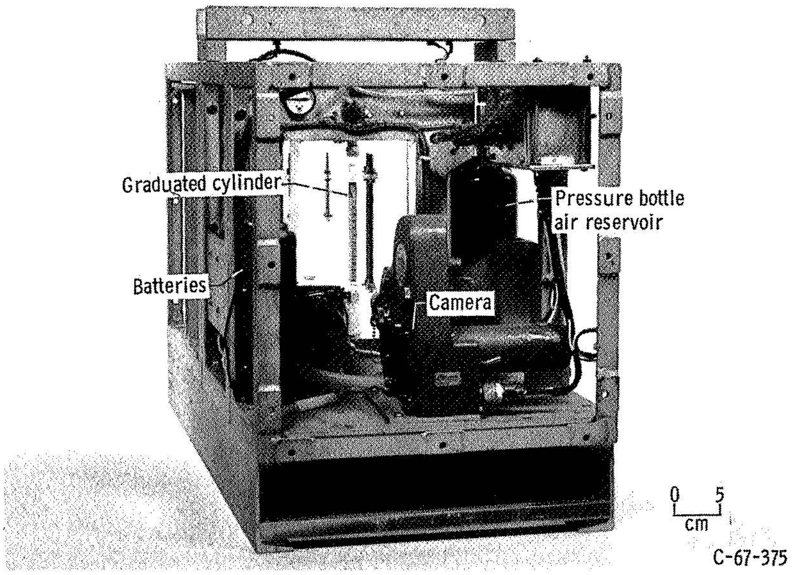
Figure 7. - Position of experiment package and drag shield before, during, and after test drop.

Experimental Package

The experiment package shown in figure 8 is a self-contained unit consisting of an experiment tank, a pumping system, a photographic system, a digital clock and an electrical system to operate the various components. Indirect illumination of the experiment tank provided sufficient light so that the behavior of the liquid-vapor interface could be recorded with a high-speed 16 millimeter motion picture camera. An air reservoir, graduated cylinder, metering valve, and a solenoid valve make up the pumping system shown in figure 9. The volume of the air reservoir was approximately 30 times greater than the largest volume of liquid removed from the graduated cylinder during the transfer operation so that no significant pressure decrease occurred. Time during weightlessness was observed by reading a digital clock having an accuracy of ±0.01 second. The clock and all other electrical components were operated through a control box and received their power from rechargeable nickel-cadmium cells.

Test Procedure

Prior to assembling the flow components, the tank and all the flow lines were first cleaned in an ultrasonic cleaner to assure that the properties of the test liquids would not be effected by contaminants. The parts were then rinsed with distilled water and



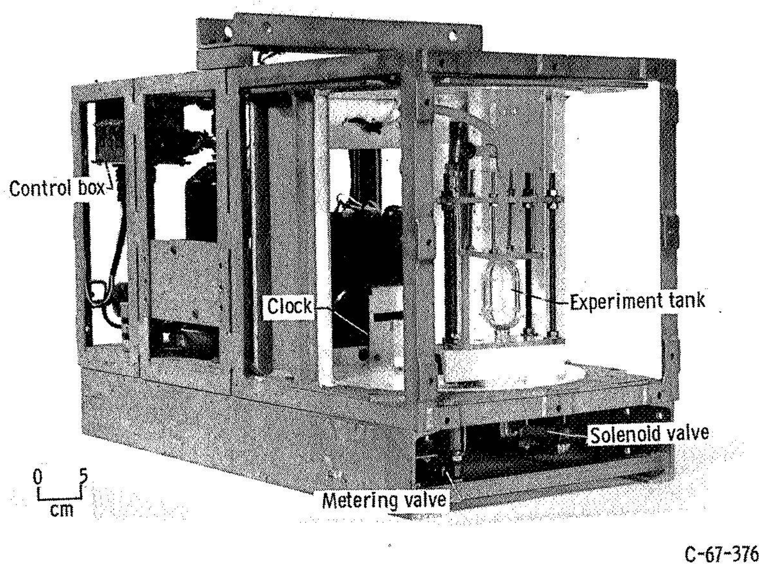


Figure 8. - Experiment package.

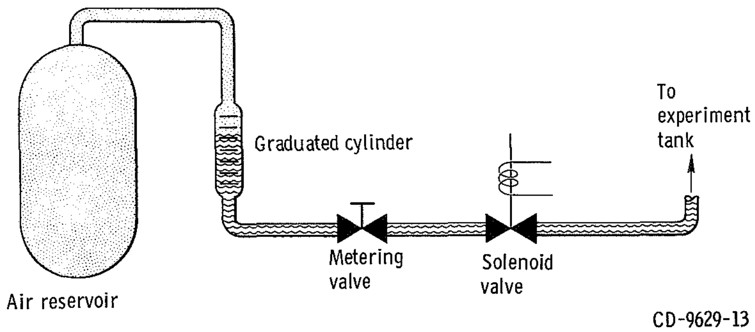


Figure 9. - Propellant flow schematic.

dried in a warm air dryer. All parts were assembled and mounted in the package.

The flow lines were filled with liquid and activated several times to remove any air that may have been trapped in the lines. The system was checked for leaks; a normal-gravity calibration test was conducted to set the desired flow rate; and the timer was set at a predetermined time increment. This set the time when the solenoid valve would open, initiating inflow of liquid to the experiment tank. The timer setting was chosen so as to start inflow when the liquid-vapor interface had reached the low point in its first pass through the zero-gravity equilibrium configuration.

Since this time, which allowed for interface formation, is a function of tank size as well as fluid properties (ref. 4), it was a limiting factor in determining the maximum tank size that could be used in the investigation. If the time required for the interface to reach the low point in its first pass through equilibrium was too large, the remaining time in weightlessness would not be long enough to adequately determine the stability of the interface.

The desired quantity of test liquid was then placed in the graduated cylinder and the experiment tank, and the required pressure was supplied to the air reservoir. The camera was then loaded and the experiment package balanced about its horizontal axes, and positioned in the prebalanced drag shield. The wire support is then attached to the experiment package through an access hole in the drag shield (see fig. 7). Properly sized spike tips were installed on the shield. Then the drag shield, with the experiment package inside, is hoisted to the predrop position at the top of the facility (fig. 5). The wire support is attached to the release system and the entire assembly is suspended from the wire. After final electrical checks and switching to internal power, the system is released. After completion of the test, the experiment package and drag shield are then returned to the preparation area.

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